Silicon Micromachined Integrated Array Instruments at Terahertz Frequencies

Goutam Chattopadhyay
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA

WS7: THz Packaging Integration Technologies, Thursday, 18 April, 2013
Terahertz (Submillimeter) Waves

Loosely defined: $1 \text{ mm} > \lambda > 100 \text{ \(\mu\)m}$

$300 \text{ GHz} < \nu < 3 \text{ THz}$

Most of the radiation in the Universe is emitted at submillimeter-wavelengths, peaking at 3 THz (if we exclude Cosmic Microwave Background).
Saturn’s moon Enceladus rains down water on Saturn!

Now we know where the water vapor in Saturn’s upper atmosphere come from!

Enceladus is the only moon in the Solar System known to influence the chemical composition of its parent planet.
Oxygen finally spotted in space

"Hidden" oxygen may be released from dust grains and ice in star-forming regions.

One of astronomy's longest-running "missing persons" investigations has concluded: astronomers have found molecular oxygen in space.

While single atoms of oxygen have been found alone or incorporated into other molecules, the oxygen molecule - the one we breathe - had never been seen.

The Herschel space telescope spotted the molecules in a star-forming region in the constellation of Orion.

Ref: Paul Goldsmith et. al.,
Observations with Herschel-HIFI of water in a young Sun-like star reveal high-velocity "bullets" moving at more than 200,000 km/h from the star. This can be compared to the velocity of a bullet from an AK47 rifle, which is 2500 km/h or 80 times slower. It is a surprise that water molecules are observed at this high velocity - they should have been destroyed in the shock where temperatures exceed 100,000 degrees.

Observations reveal that water very likely reforms rapidly in the hot and dense shocked gas. The conditions are so favorable that approximately 100 million times the amount of water in the Amazon river is formed, every second!
Herschel Space Observatory’s HIFI Instrument (JPL).

“Earth’s water may have come from comets!”
History of our Universe: Started with a Big Bang, and here we are, after 14 billion years!
Security Applications at Terahertz
Current generation heterodyne instruments are mostly single-pixel.

Mapping of large scale areas (star forming regions) is the key for future space missions.
Single Pixel Heterodyne Receivers
Stacked Silicon Micromachined Design

System-on-a-chip achieved by 3-D integration:

– Stacking each functional component reduces each layer’s complexity
– Enables a highly integrated package while still remaining modular
– Vertical routing of bias and IF connections

One Device per Layer

18mm

20mm
Stacked Silicon Micromachined Design

- **OMT and Twist**
- **90° hybrid**
- **Balanced Mixers**
- **550 GHz Triplers**
- **LO Inputs**

Simulation to outputs of Hybrids

- **Phase Difference (deg)**
- **Amplitude Difference (dB)**

Graphs showing frequency responses for 500 to 600 GHz.
Silicon Micromachining

Advantages:

• Potential for lower cost because of batch-processed device fabrication, yielding better uniformity too.

• Lithographically precise feature definitions

• Integration of bias & IF lines on silicon itself. Future potential for integrated CMOS silicon devices.

• Potential for higher density 2D transceiver arrays.

Disadvantages:

• Immature technology: need for process development.

• Challenge of wafer alignment.
Fabricated Devices

OMT

Hybrid

Twist
Fabricated Devices

OMT

Hybrid

Twist
Layer Alignment

- Enables characterization of alignment schemes
- Improves hand alignment

Axis misalignment 1um +/- 1um

Central Mark
Compression Pins

- Compression pins simplify assembly of layers
- Improves alignment accuracy compared to static pin
Evaluation of Individual Components

Precision pockets line up with bosses etched into the silicon
Multi-Pixel Radar Architecture

Antenna Array

Amplifiers, Triplers and Mixer

IF output and DC Bias

LO Power Division and Amplifier Coupling

25x25x10 mm³

34mm

24mm
Antenna Arrays

People have recently started looking into designing multi-pixel heterodyne arrays at terahertz frequencies.

Multiple copies of single pixel instruments is not the solution.

Vertical integration of subsystems will play a critical role in future terahertz array instruments.

Silicon micromachining allows integration of multi-pixel instruments in a compact package.

Alignment of the silicon wafers is an issue and is being solved through silicon compression pins.
This work was carried out at the California Institute of Technology, Jet Propulsion Laboratory, under contract with the National Aeronautics and Space Administration.